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ABSTRACT

This booklet proposes a model for learning that provides insight into the underlying physiology of the brain and suggests teaching strategies of repetition, variety and pattern, and incubation consistent with that physiology. It discusses how these three strategies can be used to enhance learning in the cognitive, psychomotor, and affective domains. The first section of the booklet provides an overview of the brain as a biological neural network. Following this section is one on artificial neural networks and how they shed light on human physiology. The next section addresses learning in the context of neural networks and describes three processes intrinsic to biological neural networks and their relation to learning taxonomies. Then recommendations are provided for applying neural networks to educational practice and a detailed illustration of these teaching strategies is provided, including recommendations such as: (1) establish learning objectives; (2) develop a shared experience; (3) employ targeted teaching and learning strategies; (4) assign drill, practice, and application exercises; and (5) test students' mastery and provide feedback. The roles of administrators and counselors in facilitating the learning process in students is also addressed. (Contains 22 references.) (CR)

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A Neural Network Guide to Teaching

by
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Introduction

Babies' brains are wired for learning? This might have been the astounded query expressed by many who read the special report in *Time* magazine in early 1997. The feature story succinctly described the physiology of the brain as a neural network, prepared before birth by genes and receptive at birth for learning.

Specifically, learning occurs when appropriate neural pathways in the brain are formed and fortified through environmental experiences. Neural pathways are information routes through the nervous system and consist of a network of nerve cells connected at minute, quasi-stable junctions called synapses. According to the neuroscientists interviewed by *Time*, intellectually stimulating experiences during the first three years of life produce a "richer" brain marked by more synaptic connections than exist in an intellectually deprived brain.

The ability to learn increases during the first 10 years of life because of the brain's ability to multiply and strengthen these neural pathways. The process continues throughout life, but the process of learning new things changes as existing neural pathways become

congested. The character of the process changes from one akin to rote memorizing to one of integration and abstraction.

By the early 1990s the neural network model of the brain began to be adapted for education. Colin Martindale (1991) published a textbook whose theme was the neural network approach to cognitive psychology. Carl Bereiter (1991) authored an article explaining the "new connectionism," another name for the neural network approach.

Both inheritance (nature) and experience (nurture) play roles in what a student can learn, in how a student learns, and in what a student actually does learn. Most students can learn a great quantity and variety of material. What accounts for a major portion of the differences we see among students is undoubtedly the result of different learning experiences. In fact, learning has been defined as the process of behavior modification *through* experience. Although teachers have little control over what students inherit, they do have significant influence over what students experience while they are in school.

It is the teacher's responsibility to find and use teaching strategies that provide students with structured experiences that maximize learning. To this end, we propose a model for learning that provides insight into the underlying physiology of the brain and suggests teaching strategies of repetition, variety and pattern, and incubation consistent with that physiology. We show how these three strategies can be used to enhance learning in the cognitive, psychomotor, and affective domains.

The neural network model of the brain can inform the instruction given by educators. Among the questions we address are:

- What role does the brain play in the overall ability of a student to learn?
- What is going on in the brain when a student learns a new skill?
- What is there about the brain and neural development that leads to some students being better at one area, such as playing a musical instrument, than in another area, such as computer science?
- What steps can educators take to facilitate the learning process in a student?
- What support must educators be given by policy makers and administrators to facilitate the learning process in students?
- What is going on in the brain of an educator when he or she teaches and seeks to improve on his or her effectiveness as a facilitator of student learning?

The next section of this fastback provides an overview of the brain as a biological neural network. Following this section is one on artificial neural networks and how they shed light on human physiology. The next section addresses learning in the context of neural networks, and we describe three processes intrinsic to biological neural nets and their relation to learning taxonomies. Then we state our recommendations for applying neural networks to educational practice and provide a detailed account that illustrates these teaching strategies.

Biological Neural Networks

Two main types of neural networks exist, biological and artificial. The human brain is a biological type; the computer is an artificial type. The neural network model described in this section rests on several premises:

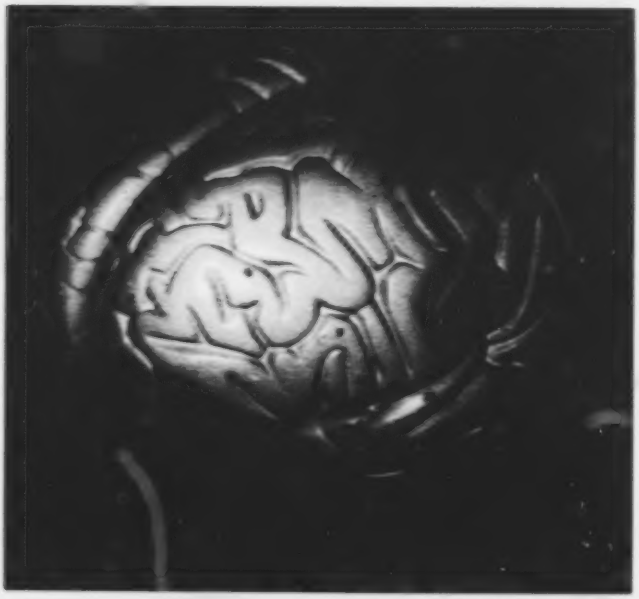
- The student has a brain and a nervous system receptive to learning.
- The nervous system is an extremely complex entity in which huge numbers of neurons are interconnected by synapses between their axons and dendrites.
- Behavior is consequential to the level of neuronal activity, the pattern of synaptic connections, and the kinds and levels of environmental stimuli being received.
- The system is plastic — that is, the level of neuronal activity and the pattern of synaptic connections adjust to stimuli and feedback provided by the environment.

What exactly is the brain? How does it function? We offer a concise sketch as partial answers to these ques-

tions. Our exposition is based, in part, on Van De Graaff and Fox (1995).

Anatomy and Physiology of the Brain

Anatomically, the brain is the uppermost portion of the central nervous system, which also includes the spinal cord. The brain appears as a grayish mass of numerous folds and grooves called convolutions, which are readily seen in the photograph of a laboratory model. The brain is soft tissue and is protected by a bony cranium. The brain contains numerous blood vessels



and cerebral spinal fluid, which act as transport systems to carry oxygen and nutrients, remove wastes, and maintain a consistent internal environment (homeostasis).

An adult's brain weighs from 3 to 3.5 pounds, about 2% of a person's body weight. About 80% of the brain's mass is the cerebrum, which consists of two convoluted hemispheres internally joined by the corpus callosum. The cerebrum is associated with higher brain functions. Its outer layer, called the cerebral cortex, stores factual information. In most persons, the left cerebral hemisphere controls analytical and verbal intelligence; the right cerebral hemisphere controls spatial and artistic skills. Besides serving cognitive functions, the cerebrum analyzes conscious sensory perceptions and controls conscious motor activities.

Each cerebral hemisphere is divided into five lobes:

1. The frontal lobes are associated with skeletal muscle control, personality, and higher intellectual processes, including reading, writing, doing mathematics, concentrating, planning, and making decisions.

2. The parietal lobes, midway in the upper cerebrum, are associated with skin and muscular sensations, understanding speech, expressing thoughts and emotions, and interpreting textures and shapes.

3. The temporal lobes, on the lower part of the cerebrum, interpret sounds and store memory of sound and sight experiences.

4. The occipital lobes, toward the back of the cerebrum, are associated with focusing the eyes, correlating visual images with previous visual experiences and other sensory stimuli, and perception of vision.

5. The insula integrate other cerebral activities and may function in memory.

Other structures of the brain also play a role in learning. The cerebellum is the second-largest portion of the brain. This convoluted structure coordinates skeletal muscle contractions for maintaining posture and muscle tone. The thalamus serves as a relay center for sensory impulses, other than smell, to the cerebral cortex. The hypothalamus regulates bodily functions, including heartbeat, temperature, and water and electrolyte balance. It also is associated with sexual response, emotions, and control of endocrine functions. The hippocampus, located in a lower part of the brain, is necessary for short-term memory and for its consolidation into long-term storage. The left hippocampus is associated with consolidation of short-term verbal memories; the right hippocampus with consolidation of nonverbal memories. Finally, the medulla oblongata connects the brain to the spinal cord and controls the activity of the autonomic nervous system.

The Nervous Systems and Neurons

The neural network of the human body is composed of the interconnected central nervous system (CNS) and peripheral nervous system (PNS). The latter includes the somatic nervous system (SNS) and the autonomic nervous system (ANS). This is the network that affects learning in the cognitive, psychomotor, and affective domains. Central to the network is the brain, the seat of learning. As previously mentioned, the CNS is com-

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posed only of the brain and spinal cord. The PNS consists of nerves, ganglia (aggregates of nerve cell bodies or centers of specialized information processing), and plexuses (networks of interlaced nerves), all of which link the CNS to other portions of our bodies (ANS) and to the external environment (SNS).

Neurons are cells that make up nerve tissue. A typical neuron is composed of a cell body, an initial segment, and the cytoplasmic extensions known as dendrites and axons. The cell body is where the nucleus, containing the neuron's genetic material, is housed. The initial segment integrates electrical information supplied by the dendrites and generates an electrical response, a nervous impulse, which travels to other parts of the nervous system over the axon. Axon and dendrite lengths vary from less than one millimeter to more than a meter. Axons and dendrites in the brain, spinal cord, and ganglia tend to be of the shorter variety, whereas axons of sensory and motor neurons in the peripheral nervous system tend to be of the longer variety.

The neuron is considered to be the fundamental unit of the nervous system. The brain is composed of about 100 billion neurons that are joined together at functional connections called synapses. A typical synapse is between axonal branches of one cell, called the presynaptic cell, and dendritic branches of a neighboring cell, called the postsynaptic cell. Neurotransmission is regulated by many kinds of neurotransmitter chemicals. Synaptic coupling occurs when a nervous impulse that arrives at the axon terminal of a presynaptic cell stimulates release of a neurotransmitter, which in turn

causes an electrical change (a postsynaptic potential) in a dendrite of a postsynaptic cell.

Postsynaptic potentials can be *excitatory* — that is, they tend to cause the initial segment of the postsynaptic neuron to generate a nervous impulse — or they can be *inhibitory* — that is, they tend to prevent the initial segment of the postsynaptic neuron from generating a nervous impulse.

Improved forensic histological techniques, ultra-high-powered microscopes, and positron emission tomography (PET) scans have given researchers new insights into the brain. According to Russell and Norvig (1995), a salient finding is that synaptic connections have the property of plasticity. They define plasticity as "long-term changes in the strength of connections in response to the pattern of stimulation" (p. 564). The strength of a synaptic connection relates to the effect the neural transmission at the synapse has on exciting or inhibiting the postsynaptic cell. Synapses located near the initial segment of the postsynaptic cell are more effective than synapses located farther away from the initial segment. Synapses that are used often to transmit information between neurons become more stable, decreasing the chance that the synapses will break. Synapses that are infrequently used become less stable, increasing the chance that the synapses will break. Axons that lead to synapses that break will grow in new and random directions and remake synapses at different locations. The making and breaking of synapses leads to a constant rearrangement of the connections in the nervous system and is the basis of all learning, memory, and forgetting.

Sensory neurons respond to physical and chemical stimuli and send their responses to the central nervous system. In the central nervous system, input information is transported by synaptic connections to a massive synaptic network of association neurons, where sensory information from all parts of the body is processed to produce a more complicated response. The response, or output, of the central nervous system will more than likely involve controlling the activity of the muscles and glands of many body systems. Thus the central nervous system effects a response through synaptic connections with motor neurons that are connected to the various muscles and glands throughout the body. These ever-changing neural pathways mediate our behavior, thoughts, and drives and are the focus of the latest research on learning.

Recent Discoveries in Neuroscience

The main thrust of recent brain research is in the area of developmental biology. Learning, memory, and forgetting are aspects of an ongoing process of development in the nervous system.

Neurons are not produced during a person's lifetime. They are developed prenatally and established at birth. What develops postnatally, especially during the first several years of life, is the growth of nerve tissue. This is a time when extensive learning is occurring. Recent studies have shown that there is a direct relationship between increased learning and an increase in the number of synapses in the brain. However, nerve tissue is

altered during the aging process. It is thought that about 100,000 neurons die each day. Mortality such as that may have an adverse effect on memory.

The *Time* article that we cited in the first section emphasized the windows of opportunity for learning. For example, babies can see at birth; yet depth perception develops around four months, when binocular vision has been conditioned from a variety of repeated visual experiences. Basic motor skills, such as reaching, grabbing, sitting, crawling, walking, and running, develop with experience during the first four years of life. Fine motor skills develop after basic motor skills. Drawing pictures and playing musical instruments aid in that development. Language acquisition develops from birth to six years of age, an optimal time for learning a second language.

The important point is that synaptic pathways in the brain are conditioned through repetition. Moreover, neural pathways conditioned early in life are readily receptive to subsequent learning experiences, which build neural connections on previously learned experiences of a similar nature.

The autonomic nervous system (ANS) is a network connected to the PNS and thereby to the CNS. This system, composed of sympathetic and parasympathetic portions, controls the skin and organs of the chest and abdomen. Stanley I. Greenspan, a child psychiatrist, is doing research that suggests the ANS is associated with affect, or emotions. He has advanced a model of development, including a novel view of intelligence, that incorporates emotion into the "hard-wired" nervous

system. Greenspan views intelligence as "the ability to create ideas from lived emotional experience, to reflect on them, and to understand them in the context of other information" (1997, p. 126). His model of cognition and affect already has proven effective in the treatment of autistic children. Basically, Greenspan's therapeutic technique helps autistic children advance from a diminished affective state to rewarding emotional experiences and then to on-target cognitive development.

A Nexus of Neural Networks

In recent years neuroscientists have been working with artificial intelligence researchers to increase the knowledge base about how the brain works. For example, Freedman (1994) reports that a computer model can learn specific patterns and store them in a fashion similar to that of the hippocampus. Then, another computer can take these newly learned patterns and construct a generalization from them, an activity akin to that of the neocortex. Other computer models are aimed at incorporating artificial emotion, making predictions based on abstracting patterns, and simulating brain damage.

The computers mentioned above are artificial neural networks (ANNs). They are the focus of intense research and development. The general process for learning that is incorporated in ANNs is similar to that used by humans. This strong similarity is not unexpected, considering the synergy between studies of the nervous system and the design of artificial neural networks. Because of the contributions of ANN learning to

our model for teaching, we devote the next section to these machines.

Artificial Neural Networks

Artificial neural networks are computers composed of multiple layers of nodes connected by links. Nodes, the fundamental units within the networks, can be constructed from solid-state components that are physically wired together; or the nodes and their connections can be etched on silicon chips. The computer also must include input and output nodes that connect to the world outside the machine and "hidden" nodes that serve as intermediaries. In addition, there are sensory attachments, such as cameras, voice units, and robotic equipment.

These neurocomputers are different from the familiar serial-processing, stored-program, personal computer. Artificial neural networks (ANNs) behave, react, self-organize, generalize, and forget, rather than execute programs composed of rule-based code. Simply stated, neurocomputers, unlike standard desktop computers, are capable of learning because they simulate the human brain and the nervous system.

Today, neural networks exist in a variety of forms. ANNs generally are considered superior to serial-

processing, stored-program computers for pattern recognition and classification and for speech and image understanding. Among applications described by Fogelman-Soulié (1995) are radar, sonar, and infrared signal processing; quality control in manufacturing; automatic diagnosis in medicine; monitoring of productivity in oil wells; analysis of particle trajectories in physics; signature identification in fraud detection; and risk analysis in finance. In recent years symbolic artificial intelligence systems are being coupled with neural networks to form hybrid systems. One such hybrid, known as KBANN, has contributed to genetic research by successfully recognizing promoters in the DNA of E. coli bacteria (Shavlik 1994).

How ANNs Work

Nodes are designed to simulate the manner in which neurons work. For example, a particular voltage is introduced to a node. This voltage is the input. If the input, or a combination of several inputs, exceeds a certain threshold, then an excitatory signal is sent to the next node. Otherwise, either no signal or an inhibitory signal is passed on. Feedback mechanisms allow the connections between nodes to be adjusted for various signal strengths.

Franklin (1995) describes a word-recognition simulation, an example of an ANN, that is based on a model developed by James McClelland and David Rumelhart. The simulation involves a small number of four-letter words. Word recognition depends on recognition of

each of the four letters that compose the word, but the input consists of the individual strokes that compose each letter. The strokes and letters are interconnected, so that each stroke is connected to each letter. And connections between the letters and words are bi-directional to accommodate feedback once letters are displayed in printout.

Even such a relatively elementary network demonstrates a complicated web of circuitry. This network requires 104 letter units, 26 letters for each of the four letter positions. Moreover, four copies of the entire set of strokes are necessary — one copy for each letter unit. Strokes that correspond to letter formation excite a letter unit; otherwise, they inhibit the connection. Once the correct letter is determined, all other letters in that position are inhibited. Likewise, each correctly formed word inhibits every other word for that position.

In neural networks, memorization occurs when a relatively small number of input-output relationships are learned. Separate pathways for information flow through the network; and as more and more items are presented, the "pressure" to share portions of pathways increases to the point that the network responds to the *relationships* among different items, rather than just to the individual items. This is abstraction, where entirely new input that conforms to the established relationships between items will elicit a correct response from the network. Networks also achieve a higher intelligent function that we call illumination. This occurs when pieces of disjointed information are integrated correctly.

The word-recognition network demonstrates these intelligent functions. For example, it demonstrates mem-

orization because it recognizes the different strokes that compose the letters. It also demonstrates abstraction by recognizing words when it is given the letters that form those words. Interestingly, this network even recognizes words for which "noisy" input is introduced. For example, when the stroke formation for the last letter in a word is partially obstructed, the network determines the correct word because of its accrued knowledge of words. This latter process is an example of illumination, putting together pieces of seemingly disjointed information.

ANNs and Human Development

J.L. McClelland has been working with a type of computer called a parallel-distributed processor (PDP) to simulate human problem solving. In one experiment, he trained a PDP to predict which side of a balance scale would go down depending on varying weights and distances on both sides of the fulcrum. He compared the PDP's performance to the developmental stages of children in earlier balance-scale experiments by Robert Siegler.

McClelland's results suggest that learning proceeds in stage-like progression, based on incremental changes that build on prior knowledge, which is similar to the learning of children. For example, three-year-old children do not do well on the balance-scale task because they cannot understand the weight or distance factors. Four- and five-year-old children perform well when only the weight varies and the distance remains constant.

Eight- and nine-year-old children have some success with varying both weights and distances. Some children 10 years of age and older understand the principle of torque: The side with the greater product of weight and distance goes down.

McClelland (1995) notes that connectionist models best explain the implicit form of cognition in which knowledge is based on performance conditioned by feedback. Implicit knowledge is exemplified by the younger children, who were able to correctly identify which side of the balance scale would go down though they were unable to explain how they got their answers. Where explicit rules are concerned — for example, the torque rule articulated by some of the older children — connectionist models need further development. Nonetheless, because explicit knowledge seems to build on implicit knowledge, the connectionist approach has a base from which to explore the relationships between these two forms of cognition.

A group of cognitive psychologists at McGill University in Canada are working with cascade-correlation networks to study developmental transitions in problem solving. In a cascade-correlation network, elements are added to simulate thinking progressions. Shultz and his colleagues (1995) studied five problems: 1) the balance scale; 2) potency and resistance, another type of balance scale; 3) seriation, or sorting objects along a dimension; 4) distance, time, and velocity; and 5) acquisition of personal pronouns in English. Their method was similar to that used by McClelland, a comparison of the network's performances with those of children in previous studies.

The McGill team found that their connectionist models captured the correct stage progressions in all of the domains they studied. Furthermore, the cascade-correlation networks exhibited gradual transitions, some stage skipping, and limited regression to earlier stages. In the last case, the backward moves were temporary. Because this kind of behavior imitates human development, these special networks show promise in helping cognitive researchers to better understand how humans think.

The Relationship Between Natural and Artificial

Artificial networks are remarkable in imitating human thinking. However, there are several striking contrasts. First, nodes can be added to an artificial neural network; but the maximum number of neurons in the human brain is present at birth. Second, network components are manufactured; neurons and synapses occur naturally. Third, ANNs cannot effectively process explicit rules specified in symbols, though some connectionist researchers are working on this problem. Also, spontaneity in linking seemingly disparate items into meaningful relationships is best performed by the biological system. One of the ways in which this process is accomplished is by illumination, a catch-all term that may include creativity.

Neural Network Learning

The model we propose comes from the relationship between neurobiology and computer design.

Three processes are fundamental to learning: memorization, abstraction, and illumination. Each process is interwoven within the respective domains of cognitive, psychomotor, and affective learning. Because the cognitive domain is the principal concern of schooling, we begin there.

When we say "pathways," we mean neural pathways. We use the word *neural* as a generic term for the nervous system, which includes neurons.

Cognitive Domain

Learning occurs through trial-and-error, when chance variations in synaptic strength are stabilized to form useful pathways between specific input-output pairs. Inputs are facts to be learned; outputs are observable concomitants of input, such as speaking and writing. Correct input-output relationships occur after appro-

priate feedback from a reliable source, such as a teacher, peer tutor, flash cards, computer program, or printed answer key. Memorization occurs when the appropriate synaptic pathways are strengthened by repetition.

The human brain is a massive parallel-data processor capable of memorizing a large number of items. In young children, with their relative paucity of experience, most items find separate individual pathways through the brain and thereby are memorized easily. Adults, with their time-gained experience, have reached a point where separate individual pathways are hard to come by. As a result, adults find memorizing a lot of facts more difficult than children do. Strategies for teaching children, adolescents, and adults need to take these differences in information-handling into consideration.

Memorization is necessary for establishing a knowledge base in elementary school students. For math, youngsters must learn how to count before they can learn addition. They must learn one-digit addition before they can master two-digit addition. In language, elementary school students must memorize the alphabet and phonemes before they can read aloud effectively. They must memorize the meanings of vocabulary words before they can comprehend what they read. Thus the knowledge base must be built on memorized facts that form the basic structure for future associations.

For any given neural network, including the brain, only a relatively small number of facts can be learned by the emergence of separate, individual pathways. Thus information flow through the network needs to be packaged in meaningful ways. Memorized facts must

be linked together to form a higher level of neural network learning called abstraction.

Abstraction takes place when the following conditions occur. First, there must be a relationship between different input-output items. Concurrently, there must be a sufficient number of items to make it impossible for an individual pathway to form for each item. Under these conditions, the new neural pathways share portions of other pathways. This sharing of already established pathways greatly reduces the number of trials needed to establish a workable pathway. As more items are presented, the "pressure" to share more and more portions of pathways increases to the point where the network responds to the relationships between the different input-output items, rather than to the individual items. When the learner has reached the level of abstraction, an entirely new input that conforms to the established relationship between items will elicit a correct response from the network.

For example, young children can learn to count by memorization, but they need abstraction in order to advance to whole-number numeration. The teacher can help the children by showing them groups of sticks, some of them bundled in tens and others left unbundled. Pattern is shown by placing the bundled and unbundled sticks close to their respective names, so that 36 is represented by three bundles and six unbundled sticks. In this way children grasp the meaning of the ten digit and the unit digit in two-digit numbers. When these children are able to assemble a particular two-digit number with sticks, or when they are able to cor-

rect the teacher who shows six bundles and five loose sticks and says "56," the children have acquired abstraction.

Whereas the process of memorization encompasses *declarative* knowledge, the process of abstraction encompasses *procedural* knowledge, which is knowing how to do something. An example is knowing how to correct the teacher when he or she deliberately makes a mistake for the purpose of evaluating students' understanding. Illumination, by contrast, exemplifies *conditional* knowledge, which is knowing when to use declarative and procedural knowledge.

Illumination occurs after preparation through abstraction and incubation. Incubation is the period of apparent rest that follows a period of active learning. During this "rest," seemingly disparate items are connected along synaptic pathways in the neural network.

Illumination builds on both memorization and abstraction. One example of illumination is creativity. For creativity to occur, diverse mental elements existing on separate pathways must be combined in a novel way. As an example, consider a ninth-grader who has learned in science class that different materials get hot faster or slower in relation to their specific heat indices. She knows that metal has a lower specific heat index than glass and should expand sooner when heated. So when the metal lid on her glass jar of jam is stuck, she thinks about her options and then runs hot water over the tightened lid until she is able to open it. If the teenager did not previously know about this technique for opening jars, she has demonstrated creativity.

Psychomotor Domain

In general, activities that require voluntary muscle control and hand-eye coordination are part of the psychomotor domain. This domain is concerned primarily with procedural knowledge. A short list of these activities includes writing, speaking, typing, riding a bicycle, driving, playing musical instruments, playing sports, dancing, and drawing. Psychomotor activities are part of all subjects; however, they are a particular focus in classes for typing, music, art, physical education, home economics, and industrial arts. Laboratory work also requires good psychomotor skills.

Memorization, abstraction, and illumination relate to psychomotor skills in the same way as they do to the cognitive domain, except more emphasis is on procedural knowledge. To achieve mastery in a psychomotor skill, the entire neural network must work in complete accord. Incoming information received by the senses is sent by nerves in the sympathetic nervous system to the appropriate processing areas of the brain. In turn, the central nervous system directs motor neurons in the peripheral nervous system to effect the corresponding action by the muscles.

As a taxonomy, psychomotor skills progress from simple perceptions and reflex actions to more complicated, skilled, and even creative movements. The "practice makes perfect" adage is true in this domain, because automatic psychomotor action is achieved by repetition over the same neural pathways. When children learn to play a musical instrument, the smoothness and polish

of their performance comes with practice as the physical movements become automatic. When they achieve a level of polish, their brains will have formed common pathways for processing many discrete, memorized skills. This is the level characteristic of abstraction. If they go on to write music in addition to playing it, then they will have reached the level of illumination. When they write brilliant scores, they will have reached the pinnacle of illumination: creativity.

Affective Domain

Emotions, feelings, attitudes, and values are part of the affective domain. Children express emotions, feelings, attitudes, and values based on their experiences. For example, when children constantly witness acceptable social behavior, such as justice to others, they are receiving information through their senses that prepares neural synapses. When they respond justly to others and are praised, while being corrected for being unjust, their responses refine these synaptic pathways. What they are learning through such "memorization" are separate instances of justice.

When children respond to enough examples and counter-examples, their neural networks integrate variety and pattern into the concept of justice. At this stage they are organizing justice into overlapping neural pathways. They have reached abstraction. And when the child has synthesized enough instances of justice to understand justice and to do justice to others, he or she has reached illumination.

Unfortunately, these stages also can apply to negative behaviors. For example, negative stereotypes regarding individuals of certain races, ethnic groups, or religions instilled in young children can extend later in life to prejudices toward groups of people.

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Neural Networks and Instructional Practice

Teachers, administrators, and counselors can implement neural network instructional strategies. To do that, they must take into account the previous experiences of each student.

Teaching is the process of applying experiential pressure to the essentially capricious process of pathway modification going on in a student's brain. Some new experiences may quickly create learning for students whose previous experiences allow the new experiences to be incorporated easily into existing neural pathways. For other students, the same new experiences will not produce easy or quick learning, because those students' previous experiences have not paved the way for the new experiences.

Learning occurs when, through a process of recurrent trial and error, chance variations in synaptic strength are stabilized to form useful pathways for input-output pairs. These pairs are items of information. Memorization (in other words, repeated experience) of a certain critical volume of information is necessary before abstraction and illumination can occur.

Teachers can do little to facilitate the initial memorization of items, other than providing a disciplined environment in which necessary drills are undertaken. Drilling students is mainly a laborious, administrative procedure that requires constant feedback. However, computer programs can be excellent and untiring generators and administrators of drills if the students are motivated to use them.

Feedback neural circuitry is established when the output of one pathway is connected back to one of its inputs. Feedback is mandatory for maintaining synaptic connections, because biochemical mechanisms within the neurons stabilize synapses with use. The probability is low for an active synapse to break, but the probability is high for an inactive synapse to break.

Length of time for drilling depends on the age of the learner and the level of the subject. Young children beginning a new subject require the most time for drill and practice. Fortunately, the brains of young children, with their relative paucity of experience, are readily receptive to forming separate individual pathways corresponding to new factual knowledge. Short, frequent, drill-and-practice sessions can be very productive.

At the other extreme, adults who are studying a subject entirely new to them find it difficult to memorize many new facts. For adult learners, open notes and books can be substituted for rote instruction. In fact, this procedure is not uncommon in college statistics courses, for example, where lengthy formulas must be applied to solve problems. However, memorization is mandatory in some cases.

When teaching adolescents, the teacher must first assess their levels of declarative knowledge. Ordinarily, drill and practice will be necessary only as entirely new topics are encountered. However, prior knowledge will need to be activated as background for new lessons; such review strengthens possibly weakened synaptic pathways. It is important to remember that recognition and recall of information, such as facts and patterns, result from the use of strongly connected pathways in the brain.

Although memorization is the foundation of learning, abstraction is the level that students must reach to perform successfully in their studies. In general, teachers can more easily facilitate abstraction than they can memorization. However, several conditions must be satisfied. First, the student should have reached a certain experiential level with information items. Second, the teacher should know what that experience is and what level of mastery has been attained. Then teachers can facilitate the mechanistic, trial-and-error, pathway building going on in the brain by placing students in situations where the possibility of making connections is enhanced. For example, students should be placed in situations in which they need to use several items of related information that are characterized by variety and pattern.

To facilitate illumination the teacher first should ensure that abstraction has occurred. Clearly structured questions should be used to help connect disparate neural pathways. Questions may be proposed in class in anticipation of a class discussion or given as a homework

or project assignment. In either case, the process of illumination must orient the student's neural network to putting "chunks" of abstract knowledge together to form coherent, meaningful knowledge that embraces the declarative, the procedural, and the conditional. This is the kind of knowledge that must be readily available for making judgments and evaluations.

Recommendations for a Neural Network Approach

We propose the following suggestions geared to the neural network approach to instruction. Most of these suggestions are basic to good teaching, but they should be founded on an understanding of the underlying brain functions that make them necessary.

1. *Establish learning objectives.* In some cases, an official curriculum provides uniform objectives. When this is not the case, teachers should develop their own clear objectives. The learning objectives may be the same for all students. However, different amounts of time must be allocated and different strategies of instruction must be developed to ensure mastery of the same objectives by different students. The less experience a student has in a topic, the more time must be allocated to the emergence and strengthening of efficient neural pathways. The learning process may be speeded if teaching is tailored to the particular experiences of the student. The teacher's job is to structure learning experiences in ways that result in students' "memorizing" the necessary information to ensure that abstraction and illumination can take place.

2. *Develop a shared experience.* A common learning experience to which all students can relate at the beginning of a lesson will focus students' attention on the subject matter. Further, such a shared experience can provide a common reference for both the teacher and the entire class. The shared experience also should inform the teacher of students' prior knowledge and skill, and it should inform students of their level of knowledge and skill.

3. *Employ targeted teaching and learning strategies.* The shared experiences should enable teachers to design strategies that advance current student knowledge and skill toward the established learning objectives. The strategies should be aimed at existing neural pathways that can facilitate the learning process. Audiovisual aids, manipulatives, computers, calculators, and other resources can be used to present information in ways that meet students' needs for input that connects to existing knowledge.

4. *Assign drill, practice, and application exercises.* Instruction should be designed to provide sufficient repetition, variety, and pattern to establish and strengthen the neural pathways necessary for learning new information. The resources invested in this activity will be different for different students with varying levels of prior knowledge.

5. *Test students' mastery and provide feedback.* Feedback about students' progress must be provided for two reasons. First, both teacher and student must be able to

judge whether timely progress is being made toward achieving the learning objectives so that they can adjust teaching and learning approaches to the experience. Second, assessment and feedback are necessary for subsequent teachers. Such knowledge also will help students with future learning.

The Roles of Administrators and Counselors

The less background knowledge of a topic that a student has, the more time it will take to make, refine, and strengthen neural connections. This means that rigid syllabi that cram too many objectives into a particular course need to be revised. For effective learning to take place, instructional time must be tailored to students' needs. This has ramifications for administrators and counselors who are involved in determining school schedules.

Administrators can help to ensure that class schedules are flexible and that teachers have realistic syllabi from which to work. Counselors can help by evaluating students' skills, when necessary, and by overseeing students' placements in classes where instruction can be adjusted to best meet their learning needs.

Another administrative duty is teacher evaluation. To ensure student success in heterogeneous classes, students of lower ability may need special tutoring. Administrators and counselors should find ways to provide academically needy students with tutorial help in whatever way is appropriate for the school. Peer tutoring during school or professional tutoring before or after school may be use-

ful in raising students' achievement. Thus teacher evaluation should be based on fairness of opportunity to learn for all students in the class.

Teachers, administrators, and counselors need to work together to guarantee that instruction takes place according to the needs of individual students. These needs are related to knowledge already existing in connected synaptic pathways. In some cases, synapses must be broken, repaired, and refined. In other cases, synapses must be made and refined. Regardless of individual students' situations, the overriding goal is mastery of realistic instructional objectives by all students.

A Recipe for Success

We provide the following example, adapted from Thompson, Smith, and Ballinger (1993), to illustrate our model. This example is suitable for a high school physical science lesson, in which the content may be integrated with language arts, other types of science, and mathematics. The lesson might extend over several class periods.

1. *Establish learning objectives.* At the conclusion of this lesson, the student should be able to:
   a. define specific heat of a substance in terms of heat energy;
   b. define specific heat of a substance in quantitative terms;
   c. describe the relationship among change in heat energy, mass, temperature, and specific heat of a substance; and

d. calculate the amount of heat gained or lost by a substance by using an equation based on its specific heat.

2. *Develop a shared experience.* Prompt students to recall their experiences at the seashore on a hot summer day. Use the query: "If the sand on the beach and the surrounding water have been in the sun for the same time, why does the sand feel hot and the water seem cool?"

3. *Employ targeted teaching and learning strategies.* First, determine what the students know from their responses to the shared-experience question. Second, pose an experiment concerning sand, water, and temperature. Ask students to anticipate the result — in other words, to develop hypotheses. Third, perform the following experiment as a demonstration:

a. Fill each of two Pyrex beakers with 50 milliliters of water at room temperature.
b. Using two thermometers, students should measure and record both temperatures.
c. Heat 50 milliliters of water and 50 grams of sand, in similar Pyrex beakers, to a temperature of 100° Celsius.
d. Pour the hot water into one of the two beakers containing water at room temperature; pour the hot sand into the other beaker.
e. Have students record the temperature of each mixture and calculate temperature changes.

This is the stage to develop critical thinking. Lead students to the idea that even though the hot water and hot

sand were at the same temperature, each contained a different amount of heat energy. The water took longer to reach 100° Celsius, because it absorbed more heat than the sand absorbed. Therefore, the hot water released more heat than the hot sand did.

State the informal and formal definitions of specific heat. The teacher should channel students' thinking toward a relevant conclusion. Inform students that the specific heat of a substance is a constant defined in terms of calories per gram per degree Celsius. Also, inform students that heat energy is measured in a relative way, according to heat gained or lost in calories. Then ask: "Are specific heat and heat energy directly or inversely related?" Students should conclude that the definition of specific heat, together with the facts given and the results of the demonstration, lead to a *direct* relationship. Further, they should have a "feel" for mass, which is a constant, and temperature, which is a variable, entering into the equation in a direct way. Therefore, students should see, at least intuitively, that multiplication is involved.

Finally, the teacher should write the equation and get students involved in doing the calculations that lead to answering the seashore question. The teacher should ask students to use the equation to calculate the changes in heat energy when the water and sand were heated from room temperature to 100° Celsius. Give students a few minutes to do the calculations. Cooperative learning groups are well-suited to this part of the lesson.

Before leaving the class, students should know that, when heated by an external source, any two substances

of equal mass will react differently to the same change in temperature. The substance with the greater heat capacity — that is, the higher specific heat — will gain more heat energy and, in turn, lose more heat energy than will the substance with the lesser heat capacity. Thus sand at the seashore, which has a lower heat capacity than does the surrounding water, heats up faster. In turn, water, with its much greater heat capacity, draws heat from bathers' bodies in addition to heat from the sun.

4. *Assign drill, practice, and application exercises.* The teacher should prepare in advance a number of practice exercises to be done after the demonstration lesson. These exercises, which can be assigned as homework, should provide variations on the pattern developed in the lesson. These exercises should not be simply "plug-and-chug" drills; they should require calculations for heat lost, heat gained, mass, temperature change, and identification of mystery substances. In the last case, identification can be based on a match between the calculated specific heat and a value in a table of specific heat values.

5. *Test students' mastery and provide feedback.* After a reasonable time for practice, which could be the same day, the next day, or later (but not so late that the topic is forgotten), the teacher should quiz students on the related topics of energy change and specific heat. The grade on the quiz will provide feedback to both students and the teacher regarding how well the students understand concepts and applications.

Conclusion

When a student learns a new skill, he or she is rearranging the synapses between neurons in the brain. Generally, the rearrangement first leads to the memorization of facts. When enough facts on separate neural pathways encounter interference, associations induced by variety and pattern are formed. Associations are formed by integrated, or shared, synaptic pathways and represent abstraction. Sometimes, after a period of mental rest (incubation), two or more abstractions are consciously synthesized to form new knowledge. This is illumination. If the knowledge produced was not previously known to the thinker, then a "byproduct" of illumination has been achieved: creativity. However, creativity also can occur when pathways are subconsciously, randomly connected.

Some students excel in playing musical instruments while others excel with computers because different students have different interests. The student must be motivated to practice constantly and thereby prepare, reinforce, and refine the synaptic pathways in the brain that support expertise.

To facilitate learning, administrators and counselors should ensure that students are placed in appropriate

classrooms. Placement tests and other evaluations are helpful in making such decisions. Classroom teachers must then work both with the entire class and with individual students. This means drilling and practice with feedback and piling up volumes of material to put stress on the memory to achieve abstraction.

Policy makers and administrators should give teachers the authority to alter learning objectives to meet the students' needs. Teachers also should be allowed to personalize their teaching to attain their stated objectives. And teachers should be given adequate time to help students achieve instructional objectives, because the natural, biological processes of memorization, abstraction, and illumination take time. Finally, teachers need support personnel to help with classroom management when instruction is individualized. Student teachers, teacher aides, retired teachers, parents, and even responsible peer tutors could help with such classroom support.

The same activities that are occurring in the brains of students also are occurring in the brain of the teacher. The teacher is forming and refining separate neural pathways by practicing teaching, which has a dimension of repetition. Seeking to improve practice means working toward abstraction. Beyond that, teachers want to find new and better ways to teach. And, certainly, teachers want to be creative. This model of the brain and learning can make a positive contribution toward those aims.

Annotated References

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This large volume is a comprehensive overview of neurobiological systems, connectionist studies, and artificial neural networks. It features 266 essays written by professionals in computer science. Topics include learning in artificial neural networks, applications and implementations, biological networks, sensory systems, and plasticity in development and learning.

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This article presents a concrete analogy to explain the "new connectionism." The author uses a Frisbee and rubber-band model to illustrate the neural network. He argues for a compromise between the rule-based, artificial-intelligence approach to knowledge and the connectionist approach that is based on the model of the neural network. The intent is to create a confluent model that would better serve the teaching profession.

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This article elucidates recent applications of neural networks, including the structure of various networks.

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This is a readable account of the artificial intelligence research. One of this book's distinguishing features is an explanation of how artificial neural networks learn.

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This article discusses the useful products that have been developed by combining neuroscience and artificial intelligence. Included is a description of silicon neurons in artificial neural networks.

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Greenspan stresses the critical need for child-rearing practices that nurture emotional well being. Having collected evidence that cognition develops along with morality and emotional experience, he advises parents and schools to ensure healthy emotional development of children by giving them the quality time they need to interact in positive ways with others. He envisions a caring, empathetic society as a solution to the selfish, violent society that is currently developing.

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This is an introductory level college textbook written from the neural-network perspective — the mind works like a brain. As such, the approach differs from an information-processing approach — the mind works like a conventional computer. Included in the content is a good section on creativity via neural nets.

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This textbook features seven underlying themes that connect all areas of science. The themes are energy, evolution, patterns of change, scale and structure, systems and interactions, unity and diversity, and stability. Content focuses on elementary physics and elementary chemistry.

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This is a technical article on perception by a neural network simulation identified as an interactive activation model. The text is illustrated with figures, including a simplified wiring diagram showing connections for processing stroke input to letter recognition and to word output.

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The author reviews his research on cognitive development, which is derived from connectionist simulation models. Balance-beam problem solving is the focal point of the discussion.

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This edition includes marginal notes and an epilog on the Perceptron-like models of connectionists. The text, which is mathematical in part, describes positive and negative aspects of Perceptrons, the simplest of learning machines.

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This article discusses research on learning styles of a large group of college undergraduates. Results suggest that distributed practice is the preferred mode for developing general cognitive skills. Massed practice is the preferred mode for association learning, such as perceptual speed tasks.

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Although the presentation is somewhat technical in its focus on recent neuroscience discoveries about the brain, the exposition is written for the general public. Implications for child care and welfare reform are included in the report.

Nelson, M.M., and Illingworth, W.T. *A Practical Guide to Neural Nets*. Reading, Mass.: Addison Wesley, 1991.

This book addresses the what, how, and when of neural networks. Included is a diskette that demonstrates neural networks. The disk operates with an IBM-compatible computer and Windows. Content extends to neurocomputers, as well as new technologies.

Pagels, H.R. *The Dreams of Reason: The Computer and the Rise of the Sciences of Complexity*. New York: Simon and Schuster, 1988.

This book focuses on three main themes: the rise of the newest order of science, the sciences of complexity; the computer as a research instrument; and the philosophy of science. Besides an enlightening chapter on connectionism and neural nets, the text covers contributions from the neurosciences, the cognitive sciences, biology, mathematics,

and anthropology. The author states that the nations who master the new sciences of complexity will be the superpowers of the 21st century.

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This large volume presents a history of artificial intelligence and a discussion of virtually every topic in the field. The text includes a section on the brain, digital computers, and neural networks.

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Shavlik describes a recent approach to machine learning that combines symbolic and connectionist approaches to artificial intelligence. The hybrid system is used in genetics research.

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These cognitive psychologists relate a variety of their research projects on cognition in problem solving as it is modeled by cascade-correlation networks. Their primary interest is how children make the transition from one developmental stage to the next.

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This textbook features five themes that connect physical science with other disciplines. The themes are energy,

stability, patterns of change, scale and structure, and systems and interactions. Content focuses on elementary physics and elementary chemistry.

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This college-level textbook is an up-to-date source of recent research in physiology and provides extensive coverage of the various biological systems, including the nervous system and brain, in conjunction with their underlying anatomy.

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This leading text in educational psychology includes a section on connectionist models, which implement neural network learning. The coverage is the same as in the sixth edition in 1995, though the earlier edition included a diagram of the Frisbee analogy to the neural network from C. Bereiter.

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The author describes neural network simulations in the context of psychological research. Topics include production and expert systems, knowledge representation, speech recognition and synthesis, visual perception and pattern recognition, and language understanding. The text is informative, though technical in part.

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